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Polarisation-independent sub-picosecond flat-top pulse generation for ultra-fast 640 Gbit/s gating

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Abstract: An 840 fs wide flat-top pulse is generated in a polarisation-independent optical differentiation scheme and used for 640 Gbit/s demultiplexing. The timing jitter tolerance is improved by a factor of three to 310 fs.

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1. Introduction

The demand for higher telecom bandwidth is steadily increasing. One way to increase the channel capacity is to increase the serial data rate as in e.g. [1]. At high bit rates, it becomes increasingly challenging to find pulse sources with sufficiently low timing jitter. Therefore it can be very advantageous to have a switch with a high tolerance to timing jitter, e.g. by the use of flat-top (FT) control pulses in an ultra-fast switch. For 160 Gbit/s, various approaches have been reported [2-4]. Beyond 160 Gbit/s, a promising scheme is based on optical differentiation in a long-period fibre grating (LPG) [5]. This scheme has the great advantage of being able to handle arbitrary pulse durations. We recently reported on demonstrations at 640 Gbit/s [6], which were successful, yet marginally so. The reasons for this are that the bandwidth of the then used LPG was only about 6 nm resulting in wider than optimum pulses (~1.4 ps FWHM with some residual pulse tails) yielding >3dB penalty relative to the 10 Gbit/s back-to-back, and that the LPG was polarisation dependent.

In this paper, we report on a significant breakthrough in the performance of our switch by significant modification of the LPG fabrication technique and more careful design of the flat-top pulse shaper for operation at 640 Gbit/s. Doing so, we were able to generate sub-picosecond (FWHM) flat-top pulses in this simple all-fiber scheme, irrespective of the input polarisation. Specifically, we create an 840 fs FWHM flat-top pulse, and show for the first time the use of a sub-picosecond flat-top pulse in a systems experiment. The pulse not only allows for error-free performance with less than 0.5 dB penalty to the 10 Gbit/s b-b, but also yields jitter tolerant operation at 640 Gbit/s. We find a 310 fs timing tolerance, corresponding to 20% of the bit duration, which is almost a factor three more than for a gaussian shaped pulse with the same 1/e-width.

2. Experimental procedure

The experimental set-up used is sketched in Fig. 1. The data signal is generated by an erbium glass mode-locked

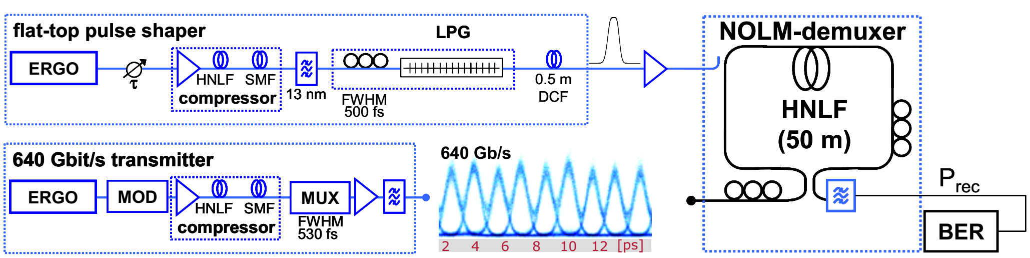

Figure 1. Setup for shaping of 840 fs flat-top pulse for 640 Gbit/s switching.

laser (ERGO) at 10 GHz and 1557 nm. The pulses are data modulated with a 2^7-1 PRBS (MOD). The data pulses are then chirped by Self Phase Modulation (SPM) in 400 m of dispersion flattened highly non-linear fiber (HNLF). The positive dispersion in the remainder of the transmitter, corresponding to 20 m SMF, linearly compresses the data pulses to ~530 fs FWHM in the resulting 640 Gbit/s data signal. An eye diagram of the 640 Gbit/s data is also shown in Fig. 1. This shows clear and open and well equalised 640 Gbit/s data eyes. The flat-top pulses are derived from an identical pulse source and pulse compressor followed by a 13-nm band-pass filter, yielding 500 fs input pulses to the LPG. A variable time delay is put in the LPG arm to align the FT-pulses with the data pulses, and a

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polarisation controller is put in front of the LPG to characterise its polarisation dependence. A 0.5 m dispersion compensating fibre is put after the LPG to trim the dispersion in the path to the demultiplexer. The FT-pulse acts as control pulse in a non-linear optical loop mirror (NOLM) including 50 m HNLF. All the HNLF is kindly provided by OFS Fitel Denmark and have a $\gamma \sim 10\ W^{-1}km^{-1}$, dispersion slope ~ 0.018 ps/nm^{2}km, zero dispersion at 1551 nm for the NOLM-HNLF, and -1.2 ps/nm/km dispersion at 1550 nm with a slope of 0.003 ps/nm^{2}km for the compression HNLFs. The control and data wavelengths are aimed at being roughly symmetrically placed around the zero dispersion wavelength in the NOLM to minimise walk-off, so the data is at 1560 nm and the FT control is at 1542 nm. The demultiplexing quality is evaluated in terms of bit error rates with the receiver power measured after the NOLM at the input to the 10 Gbit/s pre-amplified receiver.

3. Flat-top pulse generation and characterisation

The LPG has a linear transfer function of $j(\omega-\omega_0)$, essentially differentiating the electric field [5]. Spectrally offsetting the input creates a superposition of the original pulse shape with its differential, which consists of a temporal double-pulse. The original pulse can fill the gap in the double-pulse. For a certain detuning, the gap disappears completely, forming a perfect FT waveform. The transfer function corresponds to a spectral dip in terms

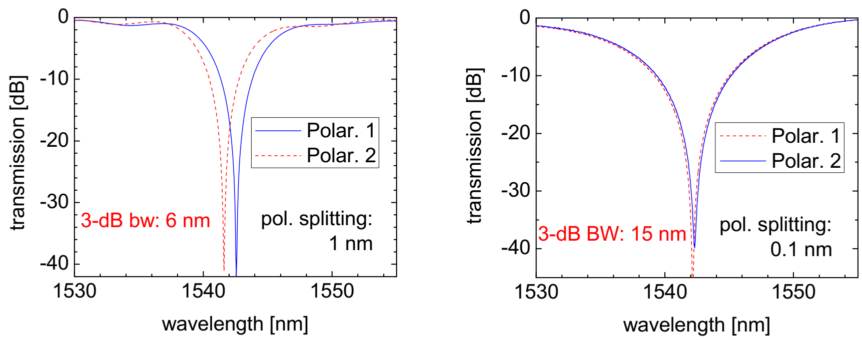

Figure 2 .Bandwidth and polarisation. Left: LPG used in [6] with 6 nm width and a 1 nm polarisation splitting. Right: New LPG for this work with 15 nm bandwidth and only 100 pm polarisation splitting.

of intensity. Fig. 2 shows these characteristic dips for the LPGs used in [6] and in this work. The bandwidth is increased to 15 nm and the polarisation dependence is reduced to only 0.1 nm, which is negligibly small for the spectral widths considered here. The LPGs are routinely made in a side-exposure of an optical fiber, which yields non-uniform refractive index change across the fiber cross-section, giving a slight birefringence. This causes the resonance frequency to vary depending on the polarisation of the input light, and results in a 1 nm polarisation splitting in the LPG used in [6]. For this paper, an inscription technique that illuminates the fiber from three sides at the same time is implemented [7]. This greatly reduces the photoinduced birefringence. Also the 15 nm bandwidth of the LPG covers the entire pulse spectrum, which ensures good flat-top pulse generation.

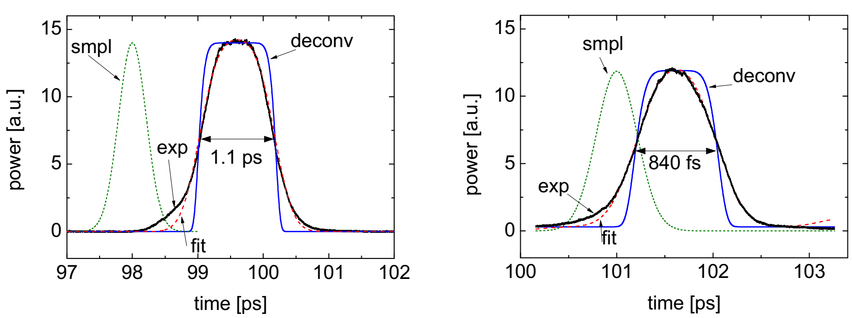

Figure 3. Cross-correlations of FT-pulses. Left: 700 fs input pulse results in 1.1 ps FT-pulse. Right: 500 fs input pulse results in 840 fs FT-pulse. The deconvoluted FT-pulses are super-gaussian of order m=3, and the width can be tuned by the input FWHM.

Fig. 3 shows the temporal output of the LPG in two cases. Fig 3 (left) is for a gaussian-shaped 700 fs FWHM input pulse, resulting in a 1.1 ps flat-top output pulse. Fig. 3 (right) is for a 500 fs input pulse, giving an 840 fs FT-pulse. The figure shows several traces: One is the measured cross-correlation ("exp"), one is the sampling pulse ("smpl"), one is the *true* FT-pulse ("deconv") when deconvoluting the sampling pulse out of the "exp"-trace and the last is the fitted curve ("fit") to the "exp"-trace, i.e. the convolution of the "smpl" and the "deconv" traces. There is very good

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agreement between the measured and the fit traces.The deconvoluted FT-pulses are in both cases super-gaussian of order m=3. To characterise the quality of the generated pulses further, BER mesurements are performed.

4. BER results

Fig. 4 (right) shows an eye diagram of all 64 OTDM channels, showing a high quality signal with all channels well equalised and with the appropriate separation, i.e. no channels are overlapping or disturbing each other. Fig. 4 left) shows the demultiplexed BER performance when using the 840 fs FT-pulse and a 700 fs gaussian pulse (made by detuning the LPG-dip away from the pulse spectrum), as they have the same 1/e-width. The demultiplexing is error-free with less than 0.5 dB penalty to the 10 Gbit/s back-to-back in the FT-case. Using the gaussian results in a 0.7 dB additional penalty, probably due to timing jitter. Note that the same channel is demultiplexed in both cases, which is ensured by detuning the LPG, whilst monitoring the demultiplexing.

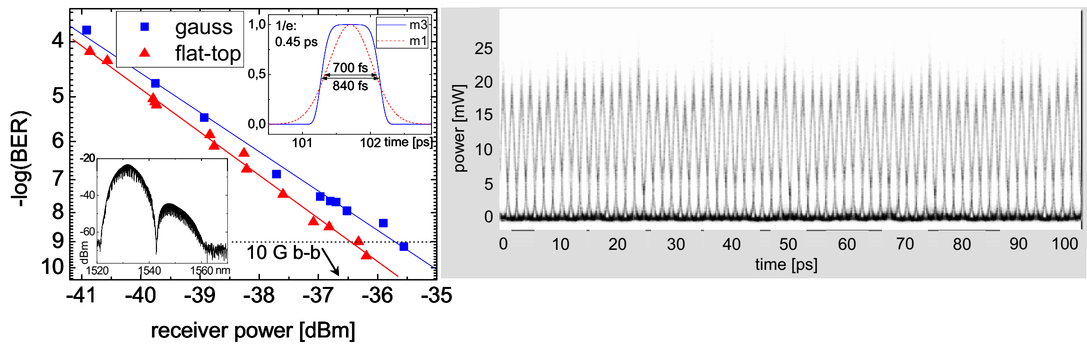

Figure 4. Left: BER performance when using FT or gauss pulse on the same channel. Insets show the super-gaussian and the gaussian control pulses, and also the spectrum of the 840 fs FT-pulse. Right: 640 Gbit/s eye diagram.

Fig. 5 shows the measured timing tolerance BER curves, as measured when displacing the control pulse with respect to the data pulses. At 5 dB receiver power above the receiver sensitivity the gauss has a 110 fs error-free

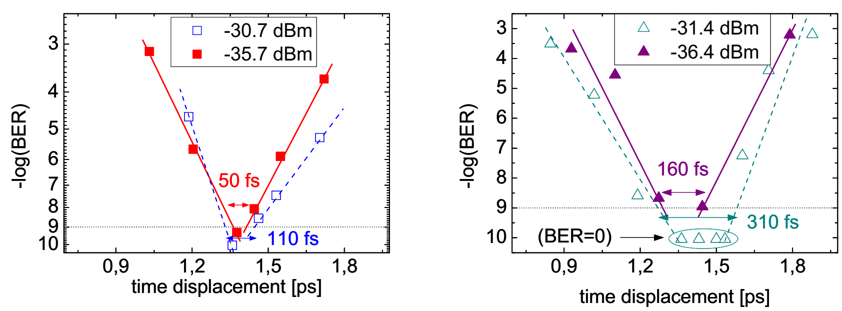

Figure 5. Timing tolerance at 640 Gbit/s, measured at the receiver sensitivity and at 5 dB more power to the receiver. Left: 700 fs gaussian control pulse. Right: 840 fs FT control pulse giving up to 310 fs tolerance with BER = 0.

timing tolerance, where the FT has a 310 fs tolerance, where the absolute BER is zero. This corresponds to the flat part of the FT pulse and is about 20% of the time slot, and almost three times greater than for the gaussian.

5. Conclusion

We have reported on a polarisation-independent long-period fiber grating used to create sub-picosecond flat-top pulses. An 840 fs pulse was created and for the first time used for 640 Gbit/s demultiplexing with <0.5 dB penalty to the back-to-back and with an error-free timing tolerance of 310 fs, i.e. 20% of the time slot. These findings clearly demonstrate the potential of the LPG-generated flat-top pulses.

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